

**Title : High frequency thin film electrical circuit element****Description**Field of the invention

5           This invention relates to a high frequency thin film electrical circuit element comprising an elongate conductor coupled magnetically with at least one layer of magnetic material extending along at least a part of the conductor above and below the conductor.

Background of the invention

10           Embedding or sandwiching the conductor of an inductive element in a magnetic material can significantly increase its inductance at a given size or reduce its size while maintaining a given inductance. Similarly, embedding or sandwiching a conductor in a magnetic material can improve containment of the magnetic field generated by current flowing along the conductor: this may be  
15           especially valuable if the conductor is formed as part of a semiconductor device such as an integrated circuit, since it can improve signal isolation from other elements of the device.

          A reduction in circuit element size is especially valuable for microscopic circuit elements made using semiconductor-type manufacturing techniques such  
20           as mask-controlled deposition and etching of materials on a support layer, since it leads to a reduction in occupied chip area which enables more devices to be produced for a given sequence of manufacturing operations and a given overall support layer ('wafer') size.

          However, ferromagnetic resonance (FMR) losses have restricted the  
25           applicability of such devices to below 1 GHz, even using high resistivity ferromagnetic materials.

          A report entitled "Soft ferromagnetic thin films for high frequency applications" by Fergen, I. et al. in the Journal of Magnetism and Magnetic Materials vol.242-  
30           245 p.146-51 April 2002 describes a study of the properties of sputtered thin films of magnetic material at high frequencies.

A report entitled "Ferromagnetic RF inductors and transformers for standard CMOS/BiCMOS" by Zhuang Y et al. in the International Electron Devices Meeting 2002 Technical Digest, IEEE 8 December 2002 p.475-478 describes an RF inductor comprising an elongate electrical conductor coupled magnetically with a thin layer of magnetic material extending along at least part of the conductor above and below the conductor, the layer having a thickness of 0.5 $\mu$ m and a lateral dimension of 100, 200, 400 or 800  $\mu$ m.

A need exists for a practical high frequency thin film electrical circuit element for high frequency applications that has a small occupied chip area.

## 10 Summary of the invention

The present invention provides an inductive element incorporating carefully chosen layers of magnetic material and a method of making an inductive element as described in the accompanying claims.

## Brief description of the drawings

15 Figure 1 is a perspective view of an electrical conductor for a high frequency thin film inductor in accordance with one embodiment of the invention, given by way of example,

Figure 2 is a sectional view of the inductor of Figure 1,

20 Figure 3 is a graph of the real and imaginary parts of the permeability as a function of frequency of a ferromagnetic material used in the inductor of Figure 1,

Figure 4 is a graph of the demagnetisation factor and the ferromagnetic resonance frequency ('FMR') as a function of an aspect ratio of a ferromagnetic material used in the inductor of Figure 1,

25 Figure 5 is a graph of the relative value of the inductance of the inductor of Figure 1 as a function of the thickness of the magnetic material,

Figure 6 is a graph of the relative value of the quality factor of the inductor of Figure 1 as a function of the thickness of the magnetic material,

Figure 7 is a more detailed sectional view of parts of two high frequency thin film inductors in accordance with further embodiments of the invention, given by way of example,

Figure 8 is a more detailed sectional view of a high frequency thin film inductor in accordance with another embodiment of the invention, given by way of example, and

Figure 9 is a more detailed sectional view of a high frequency thin film inductor in accordance with yet another embodiment of the invention, given by way of example.

#### Detailed description of the preferred embodiments

The embodiment of the invention shown in the drawings comprises an elongated conductor 1 formed in a layer of conductive material on an electrically insulating support layer 2. The electrical conductor 1 may consist of a single straight element, or a series of parallel straight elements connected at alternate ends to the adjacent elements so as to form a meander, or could be part of a planar or non-planar spiral inductor. In the embodiment of the invention shown in Figure 1, the conductor forms a spiral of generally square shape, having three and a half turns in this example, although fewer or more turns may be provided. An electrical contact pad 3 is formed in the same layer as the conductor 1 and provides a connection to one end of the conductor 1 for external circuit components. An electrical contact pad 4, also formed in the same layer as the conductor 1, is connected to the opposite end of the conductor 1 via a conductive bridge element (not shown) passing underneath the support layer 2.

The conductor 1 may be used as a self-inductance, or as part of a transformer. In order to increase the inductance of the conductor 1, it is embedded in a layer of thin film magnetic material of permeability greater than 1, preferably ferromagnetic material. (Note: the magnetic material is not shown in Figure 1, although it is shown in other Figures). The lateral dimensions of the conductor 1 extend parallel to and within the lateral dimensions of the magnetic layer 5. The magnetic layer 5 also has the characteristic of containing the magnetic flux from the conductor 1 to a large extent, improving shielding of the conductor 1 and

electromagnetic isolation of the signals flowing in the conductor. This property is particularly valuable where the conductor 1, with its magnetic layer 5, is disposed on a common support layer in proximity with other electrical components and, in some cases, it is possible for the conductor 1 to be part of an integrated circuit in which the support layer 2 is also part of the integrated circuit.

In one embodiment of the invention, the magnetic material 5 is a sputtered film of highly resistant ferromagnetic material of suitable thickness. Suitable ferromagnetic materials are alloys such as FeCoSiB and FeTaN.

In another embodiment of the invention, the material of the magnetic layer 5 is a composite material that comprises particles of ferromagnetic material densely packed in a substantially non-magnetic, electrically resistive matrix material. Such composite materials present reduced eddy current losses and the inductor presents reduced series resistance and reduced parasitic capacitance leading to high quality factor ("Q") at high RF frequencies. The magnetic particles may be magnetic nanoparticles of iron (Fe) or iron cobalt (FeCo) alloys. The matrix material may be an organic resin or ligant.

Typical permeability characteristics of the layer 5 are shown in Figure 3. The permeability is a complex value, comprising a real part  $\mu'$  and an imaginary part  $\mu''$ . At frequencies of the order of 1GHz and higher, such materials exhibit ferromagnetic resonance ("FMR"), at which the real part of the permeability drops rapidly and may go negative, and the imaginary part peaks. These characteristics limit the function of the circuit element to frequencies lower than the FMR frequency.

The permeability of the magnetic layer 5 depends upon its saturation magnetisation,  $M_s$ , which is an element for property of the magnetic material, and the anisotropy,  $H_k$ , which depends on the crystal structure and morphology of the layer. In both bulk and thin film configurations, the permeability of the material is as follows:

$$\mu = 1 + M_s/H_k \quad \text{Equation 1}$$

As shown in Figure 4, it has been found that the ferromagnetic resonance frequency FMR of the layer 5, as well as the demagnetisation factor  $N_z$ , are a

function of the aspect ratio of the layer 5, that is to say the ratio of the thickness of the layer 5 in the direction Z to its dimensions laterally in the direction of the axes X and Y.

The demagnetization factors are in general a diagonal tensor function of the sample shape. Their impact on the ferromagnetic resonance can be expressed as follow:

$$FMR = \gamma \sqrt{[H_k + (N_y - N_z)M_s][H_k + (N_x - N_z)M_s]}$$

where  $\gamma$  is the gyromagnetic ratio,  $N_x, N_y, N_z$  are the demagnetization factors of the particle and  $M_s$  the saturation magnetization,  $H_k$  is the crystal anisotropy field.

The demagnetization factors are calculated as:  $N_x + N_y + N_z = 1$  with their individual expressions for rods and ellipsoid widely calculated and tabulated (see for instance Modern Magnetic Materials, Principles and Application, R.C. O'Handley Wiley Interscience p.41)

For thin films,  $N_y = N_z = 0$  ;  $N_x = 1$  and  $FMR = \gamma \sqrt{H_k^2 + H_k M_s} \approx \gamma \sqrt{H_k M_s}$  if  $M_s \gg H_k$

For spheres :  $N_x = N_y = N_z = 1/3$  and  $FMR = \gamma H_k$

For intermediates configurations the  $N_z$  and FMR are dependent on the sample shape (aspect ratio) as depicted in figure 4.

As shown in Figure 4, for aspect ratios of 0.5 and above, the ferromagnetic resonance frequency falls sharply. In preferred embodiments of the invention, the aspect ratio is maintained substantially below 0.5 and preferably below 0.1. It will be seen that, for the example of magnetic material illustrated, the ferromagnetic resonance frequency is 1.5GHz in bulk material but is approximately 5GHz at an aspect ratio of 0.5 and exceeds 8GHz at an aspect ratio of 0.1.

Nonetheless, there is a lower limit to the useful aspect ratio of the layer 5. The smaller the aspect ratio for a given thickness of the layer, the wider are its lateral dimensions. For an example of an inductance of the order of 1 to 5nH at frequencies above 1GHz and a practical example of the layer 5 with permeability  $\mu$  of the order of 10, the thickness of the layer 5 of Figure 2 is of the order of 120

microns. The acceptable size of the lateral dimensions of the circuit element will depend on its application. However, for many applications, lateral dimensions of the order of 12mm, will be unacceptable, corresponding to an aspect ratio less than 0.01. Moreover, it will be appreciated that, even for reduced thicknesses of magnetic material that lead to reduced lateral dimensions, the improvement in FMR frequency obtained by reducing the aspect ratio gives diminishing returns at ratios much below 0.01, as shown in Figure 4. Accordingly, even in these embodiments of the invention, the aspect ratio is greater than 0.001.

In fact, the dimensions of the inductor will depend not only on the aspect ratio of the magnetic material but also on its permeability: magnetic materials may be used exhibiting permeability substantially greater than the value of 10 given for a typical material that is currently readily available.

The inductance of the conductor 1 embedded in the layer 5 relative to the same conductor surrounded by air ("LO") is shown in Figure 5 as a function of the magnetic material thickness. The quality factor of the inductor presented by the circuit element is shown as a function of thickness in Figure 6. It will be seen that, in this example, with a permeability of 10, a magnetic material thickness of 60 microns leads to an eightfold increase in inductance compared to an air core conductor 1 and a threefold increase in the quality factor Q.

Figure 7 illustrates another embodiment of the present invention, in which the electrical conductor 1 is sandwiched between a pair of magnetic layers 6 and 7 on the support layer 2, instead of being embedded in a single layer 5. In the example shown in the upper part of Figure 7, similar to the embodiment of Figure 2, the layer 5 has a thickness of 120 microns and, with an aspect ratio of 0.1, has lateral dimensions of 1.2mm. In the embodiment of the invention shown in the lower part of Figure 7, with two layers 6 and 7, for the same overall thickness of 120 microns, and for an aspect ratio less than 0.1 for each of the layers 6 and 7, the lateral dimensions of the layers 6 and 7 are of the order of 600 microns. In this embodiment of the invention, the layers 6 and 7 are interconnected magnetically by magnetic interconnections 8 and 9 extending on each side of the conductor 1 along substantially all its length. A typical lateral dimension for the magnetic interconnections 8 and 9 is 60 microns. It will be appreciated that Figure 7 shows

views in cross-section of the conductor 1. In each case, the layers 5, 6 and 7 of magnetic material as well as the magnetic interconnections 8 and 9 are bounded by dielectric material 10.

It will be appreciated that current flowing along the conductor 1, that is to say perpendicular to the plane of the drawing, will generate magnetic flux circularly around the conductor and accordingly contained in the transverse extent of the layers 6 and 7 and in the interconnections 8 and 9.

It will be appreciated that the embodiment shown in the lower part of Figure 7 with two magnetic layers 6 and 7 offers an improvement in aspect ratio for each of the layers for a given lateral dimension compared to the embodiment shown in the upper part of Figure 7. A further improvement in aspect ratio of the magnetic layers may be obtained as shown in Figure 8 for elongate conductors that are part of a spiral inductor by adding a further magnetic layer 11 above the magnetic layer 6 and a further magnetic layer 12 below the magnetic layer 7, the layers 6, 7, 11 and 12 being separated by dielectric material 10 as before.

As shown in Figure 8, the magnetic interconnections 8 and 9 between the superposed magnetic layers 6 and 7 and, in the case of the structure shown in Figure 8 the layers 11 and 12, need not be disposed immediately next to each turn of the conductor 1, especially in the case of a spiral configuration. In this embodiment of the invention, a magnetic interconnection is made between the layers 6, 7, 11 and 12 within the centre of the spiral of the conductor 1 at 13 and a magnetic interconnection is formed outside this spiral substantially all the way around it, at 14. In this embodiment of the invention, the magnetic connections 13 and 14 are formed by vias, formed by depositing magnetic material into holes etched in the dielectric material 10. In an alternative embodiment shown in Figure 9, the magnetic interconnections 13 and 14 are formed by plugs in which the magnetic material is grown within apertures in the dielectric 10 in mono-block configuration.

It will be appreciated that the electrical circuit device as shown in the drawings may be used in electrical circuit apparatus together with devices that are responsive to the inductance the electric circuit device presents to a periodic current flowing along the conductor.